WET SCRUBBING INTENSIFICATION APPLIED TO HYDROGEN SULPHIDE REMOVAL IN WASTE WATER TREATMENT PLANT

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Abstract

Hydrogen sulphide removal in a Waste Water Treatment Plant at semi-industrial scale in a compact wet scrubber has been investigated. The gas residence time in the scrubber was reduced to 30 ms using a NaOCl caustic scrubbing solution. The contactor is composed of a wire mesh packing structure where liquid and gas flow co-currently at high velocity (> 12 $m.s^{-1}$). H_2S removal percentages higher than 95% could be achieved whereas a moderate pressure drop was measured (< 4000 Pa). Both the hydrodynamic and chemical conditions can influence the efficiency of the process. Correlations were developed to predict both the pressure drop and the H_2S removal efficiency at given operating conditions.

Résumé

Le traitement du sulfure d'hydrogène dans un laveur de gaz compact a été étudié à l'échelle semi-industrielle en station d'épuration. Le temps de contact dans le laveur est réduit à une trentaine de ms en utilisant une solution d'hypochlorite de sodium à pH basique. Le contacteur se compose d'une structure tissée métallique dans laquelle le gaz et le liquide circulent à co-courant et grande vitesse (> 12 $m.s^{-1}$). Un abattement de l'H_2S de plus de 95% peut être obtenu avec une perte de charge modérée (< 4000 Pa). A la fois les conditions chimiques et hydrodynamiques influencent les performances de traitement. Des corrélations ont été développées pour prédire la perte de charge mais aussi l'abattement dans des conditions opératoires données.

Keywords: Absorption, chemical scrubbing, compact scrubber, hydrogen sulphide, odour control.

INTRODUCTION

Hydrogen sulphide is the major compound involved in odour emissions from WWTPs (Gostelow, 2001). The strategy applied in WWTPs to reduce odour emissions consists to ventilate the odorous stages (pre-treatment, biological aeration, sludge treatment, etc) and to bring the collected air into a single odour control unit in which different processes can be implemented (Busca and Chiara, 2003). The most common process used is the packed towers, in which pollutants are removed by chemical scrubbing (Bonnin, 1991 ; Chen et al., 2001). Chemical scrubbing involves pollutant mass transfer in an aqueous phase and subsequent reactions with acidic, basic or oxidant reagent(s). Most of the time, H_2S is oxidised by sodium hypochlorite (NaClO) in an alkaline solution ($pH \geq 9$):

$$H_2S + 4\ NaOCl + 2\ NaOH \rightarrow Na_2SO_4 + 4\ NaCl + 2\ H_2O \quad (1)$$

H_2S consumption in the liquid phase allows to maintain a driving force in order to achieve mass transfer. Moreover, when the reaction kinetics is fast compared to the mass transfer kinetics, mass transfer enhancement is involved.

Chemical scrubbing in packed towers has revealed high investment and operating costs (Couvert et al., 2008). Indeed, it implies the construction of high and large wet scrubbers. Moreover, long and expensive pipes and powerful fans are necessary to bring the waste air to the odour control unit. An alternative leading to the reduction of investment and operating costs could consist in treating odorous gas near each emission source in compact scrubbers in which the fluid residence time is significantly shorter. Process intensification, through mass transfer and superficial velocity enhancement inside the contactor, allows to decrease the reactor size and the fluid residence time.

The key element of the new Aquilair Plus^{TM} process is a patented high voidage contactor specially adapted to compact wet scrubbing (Sanchez et al., 2007a ; Biard et al., 2009a). This down flow co-current contactor consists of a wire mesh packing structure where gas flows at high velocity (U_{SG} > 12 m.s^{-1}). The liquid, swept along by the gas, collides with the wire mesh and is dispersed into fine droplets. At the laboratory scale, high mass transfer rate has been demonstrated for a moderate pressure drop (Sanchez et al., 2007b). The gas residence time could be reduced to less than 50 ms instead of about 1 or 2 seconds in packed towers to treat H_2S (Sanchez et al., 2007c). At the laboratory scale, an increase of the superficial gas velocity (U_{SG}) and in a minor extent of the superficial liquid velocity (U_{SL}) led to better interfacial area (a^0) and gas and liquid mass transfer coefficients (k_Ga^0 and k_La^0) due to a higher energy loss (Sanchez et al., 2007b ; Biard et al., 2009b).

The aim of this study was to test the potentialities of the process at the semi-industrial scale (designed to treat gas flow rates Q_G ranging between 1500 and 2000 m^3.h^{-1}) with a real gaseous effluent extracted from a WWTP. Scale-up difficulty is due to wall effects reduction at larger contactor sizes, which can induce both lower liquid dispersion and mass transfer rate. Between the laboratory and the semi-industrial scales, the spatial disposition of the wire meshes was modified to provide higher tortuosity. Both the pressure drop (ΔP) and the H_2S removal percentage were determined versus several parameters. The influence of the superficial gas velocity (U_{SG}), the superficial liquid velocity (U_{SL}), the pH, the sodium hypochlorite concentration of the scrubbing liquid ([ClO^-]) and the H_2S inlet concentration ($[H_2S]_{G,i}$) was characterised. A model was developed in order to predict H_2S removal efficiency and pressure drop in the scrubber.

MATERIALS AND METHODS

The contactor is composed of a wire mesh structure of 200 mm diameter (void fraction ≈ 99.0%). The initial height (H_r) of the packing was 600 mm but after the first experiments, the packing was compressed to 500 mm. The polluted air was pumped from the extraction pipe of the WWTP with a fan (AEIB) (Figure 1). By opening a valve placed before the fan, it was possible to dilute polluted air with clean air to modify the inlet H_2S concentration ($[H_2S]_{G,i}$ in ppmv: Part Per Million by Volume). The gas flow rate Q_G was measured and controlled by means of a Pitot Tube (Deltabar S PMD 70 from Endress Hauser) and a frequency variator (Allen Bradley). The liquid injection upstream the contactor was insured by a spray nozzle SpiralJet (Spraying System). A 400 L tank allowing to store the scrubbing liquid and to separate the gas-liquid mixture was placed downstream the contactor. A droplet separator was placed downstream the tank before emission in atmosphere (Horus Environnement). The storage tank was filled with ground water previously softened. Reagents (NaOCl and NaOH provided by Brenntag) were pumped from 1000 L tanks to the storage tank by two metering pumps Gamma L (Prominent). The scrubbing liquid was recirculated to the top of the contactor by a centrifugal pump (MDFL from Iwaki) and the liquid flow rate was controlled by an electromagnetic flowmeter (Promag 10 P from Endress Hauser).

A bypass located after the recirculation pump allowed the measurement of the pH, Redox, temperature and conductivity of the scrubbing liquid by specific probes (Endress Hauser). The pH and the hypochlorite concentration of the scrubbing liquid, clean water supply and drain were regulated respectively by the pH, the Redox and the conductivity measurements. Pressure measurements upstream and downstream the contactor involved two pressure sensors Cerabar S PMC 71 (Endress Hauser). The H_2S concentration was continuously measured upstream ($[H_2S]_{G,i}$) and downstream ($[H_2S]_{G,o}$) the contactor by

means of two electrochemical sensors Polytron (Dräger). The H_2S removal efficiency was defined as:

$$Eff = \frac{[H_2S]_{G,i} - [H_2S]_{G,o}}{[H_2S]_{G,i}} = 1 - \frac{[H_2S]_{G,o}}{[H_2S]_{G,i}} \quad (2)$$

Results and discussion

Influence of the hydrodynamic conditions on the pressure drop and the H_2S removal

Through the transparent PVC pipe contactor, a strong dispersion of the liquid into small droplets was observed for U_{SG} higher than 13-14 $m.s^{-1}$. The ratio L/G, which represents the ratio of the recirculated liquid mass flow rate and the treated gas mass flow rate, is generally close to 3 when H_2S is treated in packed columns (Bonnin, 1991). The pressure drop ΔP was measured for $600 < Q_G < 2800$ $m^3.h^{-1}$ and $3500 < Q_L < 8000$ $L.h^{-1}$ (L/G from 1.1 to 11.2). It could be observed that ΔP strongly increased with U_{SG}, since the gas is the continuous phase, and with a minor extent with U_{SL} (Figure 2). This energy loss is partly transferred to the liquid to achieve a better liquid dispersion and mixing. As a consequence, when U_{SG} increases, mass transfer rate increases, leading to an improvement of the H_2S removal efficiency (Figure 3). Hence, a compromise must be realised for the selection of U_{SG} in order to limit the pressure drop to ensure the process economic viability. The pressure drop per reactor height unit ($\Delta P/H_r$) could be well correlated to the gas and liquid superficial velocities U_{SG} and U_{SL}:

$$\frac{\Delta P}{H_r}(Pa.m^{-1}) = 285.7 \times U_{SG}^{1.68} \times U_{SL}^{0.47} = 11.9 \times U_{SG}^{2.15} \times \left(\frac{L}{G}\right)^{0.47} \quad (3)$$

The determination coefficient (R^2) between the experimental and the predicted pressure drops is 99.94 %. However, this equation is valid only for this packing geometry and diameter and should not be used for scale-up.

Otherwise, Figure 4 demonstrates that an increase of U_{SL} (proportional to L/G) at a given gas flow rate induces a significant better H_2S removal. This evolution could be attributed to a better hydrodynamic behaviour. Indeed, Sanchez et al. (2007a) demonstrated at the laboratory scale that k_La^0 increases with the liquid velocity (or flow rate). Moreover, L/G increasing implies that more liquid flows in the contactor (the liquid hold-up increases), which allows to limit the pH and hypochlorite concentration decrease due to the oxidation reaction. However, increasing the liquid flow rate generates a higher pressure drop and consumes more electrical power for the recirculation, which leads to a more expensive operation.

Influence of the chemical conditions on the H_2S removal

Chemical conditions can notably influence the H_2S removal. Now, no significant variation of the H_2S removal was observed when the pH varied between 9.5 and 11 (not presented here). However, for a pH close to 9.5, the formation of a yellow precipitate of colloidal sulphur was observed whereas for a pH close to 11, the formation of a white precipitate of carbonates could be noticed (due to the reaction between NaOH and CO_2 present in atmospheric air). Then, all the results presented in this paper were performed with a pH ranging between 10 and 10.5 (low and high pH thresholds of the regulation). Figure 4 demonstrates a positive influence of the sodium hypochlorite concentration on the H_2S

removal. When the hypochlorite concentration increases, the oxidation kinetics improvement favours H_2S oxidation in the liquid film which enhances the removal efficiency. This result is particularly interesting considering that it is a low cost operating solution comparing to an increasing of U_{SG} and U_{SL}. Several experiments were carried out for U_{SG} =14.1 $m.s^{-1}$, U_{SL} = 0.093 $m.s^{-1}$, 10 < pH < 10.5 and $[ClO^-] \approx 3\ g.L^{-1}$, but with $[H_2S]_{G,i}$ varying from 6 to 80 ppmv. The H_2S removal was not significantly different and close to 96 %. The H_2S removal is consequently independent of the inlet concentration. However, one has to keep in mind that working with high inlet concentration favours hydroxide anion and hypochlorite consumptions in the scrubber. Consequently, the amount of H_2S treated must be lower than twice the amount of hydroxide anion and 4 times the amount of hypochlorite in the scrubbing liquid at the inlet. With a classical H_2S inlet concentration in WWTP of 5-6 ppmv, it is therefore possible to reach an H_2S outlet concentration ranging between 0.1 and 0.2 ppmv, which is close to the values that deodorisation unit designers guaranty (Verguet et al., 2008).

H_2S removal modelling

Assuming a plug flow of the gas phase, in an elementary contactor height (dz in m), the H_2S transferred flow (dN in $mol.s^{-1}$) can be expressed as:

$$dN = k_L a^0 E\left([H_2S]_L^* - [H_2S]_L\right) S_{col} dz = K_L a^0 \left(\frac{[H_2S]_G}{H'_{H_2S}} - [H_2S]_L \right) S_{col} dz \qquad (4)$$

k_L and K_L are respectively the local and overall liquid mass transfer coefficients ($m.s^{-1}$), a^0 is the volumetric interfacial area ($m^2.m^{-3}$), S_{col} the contactor section (m^2), $[H_2S]_L^*$ the H_2S concentration in the liquid phase at the gas-liquid interface ($mol.m^{-3}$) and $[H_2S]_L$ the H_2S

concentration in the bulk of the liquid (mol.m^{-3}). H'_{H_2S} is the Henry's law constant in water of H_2S at 293 K (= 0,363 mol L^{-1} / mol L^{-1}). E is the enhancement factor, equal to the rate of H_2S transferred when the reaction occurs divided by the rate of H_2S transferred when no reaction occurs ($E \geq 1$). K_L is linked to k_L and k_G (the local liquid and gas mass transfer coefficients) and E by:

$$\frac{1}{K_L} = \frac{1}{Ek_L} + \frac{1}{H'_{H_2S}k_G} \quad (5)$$

Oxidation of H_2S by hypochlorite at basic pH is fast and happens in the liquid film at the vicinity of the gas-liquid interface (Danckwerts, 1970). It means that H_2S is completely consumed in the liquid film by the oxidation reaction, leading to $E >> 1$ and $[H_2S]_L \approx 0$. In this case, the first ratio of the right-hand terms of the Equation (5) may become negligible (instantaneous surface reaction) showing that all the resistance for mass transfer can be located in the gas film. However, the results demonstrated that the removal efficiency increased with the hypochlorite concentration, i.e. with the reaction kinetics, which clearly shows that a part of the resistance for mass transfer is still located in the liquid film and can not be neglected. Consequently, E must be estimated and depends on two dimensionless numbers: the Hatta number for a 2nd order kinetics (Ha) and the enhancement factor for an infinitely fast reaction (E_i) (Danckwerts, 1970):

$$E = Ha = \frac{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}}{k_L} \quad \text{and} \quad E_i = \frac{D_{ClO^-,w}[ClO^-]}{D_{H_2S,w}[H_2S]_L^*} \quad (6)$$

k_{ox} is the apparent kinetics constant ($L.mol^{-1}.s^{-1}$) of the oxidation reaction and $D_{H_2S,w}$ and $D_{ClO^-,w}$ are respectively the diffusion coefficients of H_2S ($1.6\ 10^{-6}\ m^2.s^{-1}$) and ClO^- ($1.3\ 10^{-6}\ m^2.s^{-1}$) in water. The Hatta number represents the maximum pollutant conversion in the liquid film compared with its maximum transport through the film.

According to usual hypochlorite concentrations in the scrubbing liquid (> 0.1 $g.L^{-1}$), hypochlorite is in great excess comparing to hydrogen sulphide at the gas-liquid interface. In this case, the kinetics is pseudo-first order and the enhancement factor E is equal to Ha considering that this last number is large (see Table 1) but significantly lower E_i (which is in the range 4 000-92 000 at the scrubber inlet, depending on $[ClO^-]$ and $[H_2S]_{G,i}$).

The amount of hydrogen sulphide treated in the scrubber is negligible comparing to the amount of hypochlorite at the inlet. The hypochlorite concentration, and by the way the Hatta number, are consequently constant in the scrubber, assuming that k_{ox} does not depend in a great extent of the pH which should decrease due to the hydroxide anion consumption. Therefore:

$$\frac{1}{K_L} = \frac{1}{k_L \frac{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}}{k_L}} + \frac{1}{H'_{H_2S} k_G} = \frac{1}{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}} + \frac{1}{H'_{H_2S} k_G} \quad (7)$$

According to the Equation (7), the Equation (4) can be rewritten:

$$dN = \frac{a^0}{\frac{1}{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}} + \frac{1}{H'_{H_2S} k_G}} \frac{[H_2S]_G}{H'_{H_2S}} S_{col} dz \quad (8)$$

By integration considering the height of the scrubber (H_r), an analytical equation of the overall flow of H_2S transferred is deduced:

$$N = \frac{a^0}{\frac{H'_{H_2S}}{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}} + \frac{1}{k_G}} \frac{[H_2S]_{G,i} - [H_2S]_{G,o}}{\ln\left([H_2S]_{G,i} / [H_2S]_{G,o}\right)} S_{col} H_r \quad (9)$$

The gas phase mass balance between the inlet and the outlet leads after rearrangement to the equation (10):

$$Eff = 1 - \frac{[H_2S]_{G,o}}{[H_2S]_{G,i}} = 1 - \exp\left(- \frac{a^0}{\frac{H'_{H_2S}}{\sqrt{D_{H_2S,w}[ClO^-]k_{ox}}} + \frac{1}{k_G}} \frac{H_r}{U_{SG}} \right) \quad (10)$$

This equation shows that the removal efficiency depends on the liquid dispersed state (through a^0), the turbulences in the gas phase (through k_G) and the oxidation kinetics (through the product of $[ClO^-]$ and k_{ox}). Moreover, the efficiency is not influenced by the absorption rate and the inlet H_2S concentration while hypochlorite and hydroxide anions are in excess. At the laboratory scale (Sanchez et al., 2007b), and considering that the surface tension, density and viscosity of the scrubbing liquid are constant in the scrubber, hydrodynamic study demonstrated that a^0 is a power law function of the superficial velocities: $a^0 = A \cdot U_{SG}{}^{\alpha} \cdot U_{SL}{}^{\beta}$ with A, α and β three constants. Then, the Equation (10) can be rewritten:

$$Eff = 1 - \exp\left(- \frac{A \cdot U_{SG}{}^{\alpha-1} \cdot U_{SL}{}^{\beta}}{\frac{H'_{H_2S}}{\sqrt{D_{H_2S,eau}[ClO^-]k_{ox}}} + \frac{1}{k_G}} H_r \right) \quad (11)$$

k_G should be influenced by U_{SG}. However, this variation can be neglected assuming that U_{SG} has been slightly modified (from 14.1 to 18.6 $m.s^{-1}$). Therefore, k_G can be considered as a constant. In the equation (11), A, α, β, k_G and k_{ox} are unknown. Due to the high H_2S oxidation kinetics, k_{ox} should be in the range 10^6 - 5×10^8 $L.mol^{-1}.s^{-1}$. Consequently, A, α, β and k_G have been determined (Table 1) for different values of k_{ox} in this range by numerical fitting by the least square method trying to minimise the residual:

$$\text{Residual} = \frac{1}{M}\sum_{i=1}^{M}\left(\frac{Eff_{exp} - Eff_{mod}}{Eff_{mod}}\right)^2 \text{ with } M = 18 \text{ the number of experimental data} \qquad (12)$$

The model correlates with a good agreement the experimental results whatever the value of k_{ox} selected with an average error lower than 1 % (Table 1). It demonstrates that assuming k_G as a constant is not aberrant. When the selected value of k_{ox} decreases, a^0 increases to compensate the lower enhancement by chemical reaction. At the laboratory scale, for similar superficial velocities, the average interfacial area and gas side mass transfer coefficient were respectively in the range of 1500-2000 $m^2.m^{-3}$ and 0.1-0.2 $m.s^{-1}$. These values would be reached at the semi-industrial scale for a k_{ox} equal to 6×10^6 $L.mol^{-1}$ s^{-1}. However, this value should be considered with care since the scale difference between the laboratory and this study (and consequently the difference of Reynolds Number) may lead to significant variations of the ranges of a^0 and k_G.

Pressure drop and removal efficiency simulations

Using Equations (3) and (11), simulations of the pressure drop and the removal efficiency for different operating conditions can be achieved. In order to limit the operating

cost of the process, a low value of U_{SG} (but sufficient to insure a strong liquid dispersion $\Rightarrow$ $U_{SG} > 13$ m.s^{-1}) must be selected. Consequently, two simulations have been realised at 13.3 and 14.1 m.s^{-1} (respectively 1500 and 1600 m^3.h^{-1}) using $k_{ox} = 6 \times 10^6$ L.mol^{-1}.s^{-1} (Figure 5). The choice of the quintet A, a, b, k_G and k_{ox} does not influence the results of the simulation. Simulations confirm that the removal efficiency increases significantly with the hypochlorite concentration when lower than 3 g.L^{-1}. Moreover, the removal efficiency increases strongly with the L/G ratio until 5. Using a hypochlorite concentration and a L/G ratio higher than 3 g.L^{-1} and 5 is not necessary whatever the gas superficial velocity. Using such operating conditions, the removal efficiency reaches 95 % for a moderate pressure drop which remains lower than 3500-4000 Pa (maximal pressure drop to insure the process economic viability).

CONCLUSION

A new compact chemical scrubber was implemented in a WWTP. Results showed that both hydrodynamic and chemical conditions significantly influence the H_2S removal. A model was developed to predict the pressure drop and the H_2S removal at any given operating condition. An interesting economic compromise was deduced for a moderate gas velocity and a high hypochlorite concentration. The new packing has not been optimised yet and some improvement of the structure would certainly offer a lower pressure drop for a similar mass transfer rate. To insure a high level of deodorisation, two scrubbers in series could be implemented but the increasing of the pressure drop must be taken into account.

NOMENCLATURE

[A]	concentration of the compound A
A, α and β	coefficients determined by numerical resolution
a^0	interfacial area related to the volume of the contactor ($m^2.m^{-3}$)
$D_{H_2S,w}$	diffusion coefficient of H_2S in water ($m^2.s^{-1}$)
dz	infinitesimal height of contact (m)
E	enhancement factor
E_i	enhancement factor for an infinitely fast reaction
Eff	H_2S removal efficiency (%)
Ha	Hatta number
H'_{H_2S}	H_2S Henry's constant in water
H_r	height of the contactor (m)
k_G (K_G)	(overall) gas phase mass transfer coefficient ($m.s^{-1}$)
k_L (K_L)	(overall) liquid phase mass transfer coefficient ($m.s^{-1}$)
k_Ga^0 (K_Ga^0)	(overall) gas phase volumetric mass transfer coefficient (s^{-1})
k_La^0 (K_La^0)	(overall) liquid phase volumetric mass transfer coefficient (s^{-1})
k_{ox}	kinetics constant of H_2S oxidation by hypochlorite at basic pH ($L.mol^{-1}.s^{-1}$)
L/G	ratio of liquid and gas mass flow rates
N (dN)	(infinitesimal) flow of H_2S transferred ($mol.s^{-1}$)
Q_G (Q_L)	gas (liquid) volume flow rates ($m^3.h^{-1}$ or $m^3.s^{-1}$)
S_{col}	section of the contactor (m^2)
U_{SG} (U_{SL})	gas (liquid) superficial velocity ($m.s^{-1}$)
WWTP	Waste Water Treatment Plant

Greek letters

ΔP	pressure drop (Pa)

Indices

i	inlet
G	gas
L	liquid
o	outlet
*	interface

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Figure captions

Figure 1. Set-up scheme.

Figure 2. Pressure drop inside the scrubber versus U_{SG} for different U_{SL} (Q_L = 3.5, 5.0, 6.5 and 8.0 $m^3.h^{-1}$).

Figure 3. H_2S removal and pressure drop versus U_{SG} (L/G = 3.5 ; 40 < $[H_2S]_{G,i}$ < 50 ppmv ; $[ClO^-] \approx 1.5$ $g.L^{-1}$; 10 < pH < 10.5).

Figure 4. H_2S removal and pressure drop versus L/G (U_{SG} =15 $m.s^{-1}$; 40 < $[H_2S]_{G,i}$ < 50 ppmv ; 10 < pH < 10.5).

Figure 5. Simulation of H_2S removal and pressure drop for two gas superficial velocities (U_{SG} = 13.3 $m.s^{-1}$ (Q_G = 1500 $m^3.h^{-1}$) and 14.1 $m.s^{-1}$ (Q_G = 1600 $m^3.h^{-1}$)) for $2 \leq L/G \leq 6$ and $1 \leq [ClO^-] \leq 4$ $g.L^{-1}$.

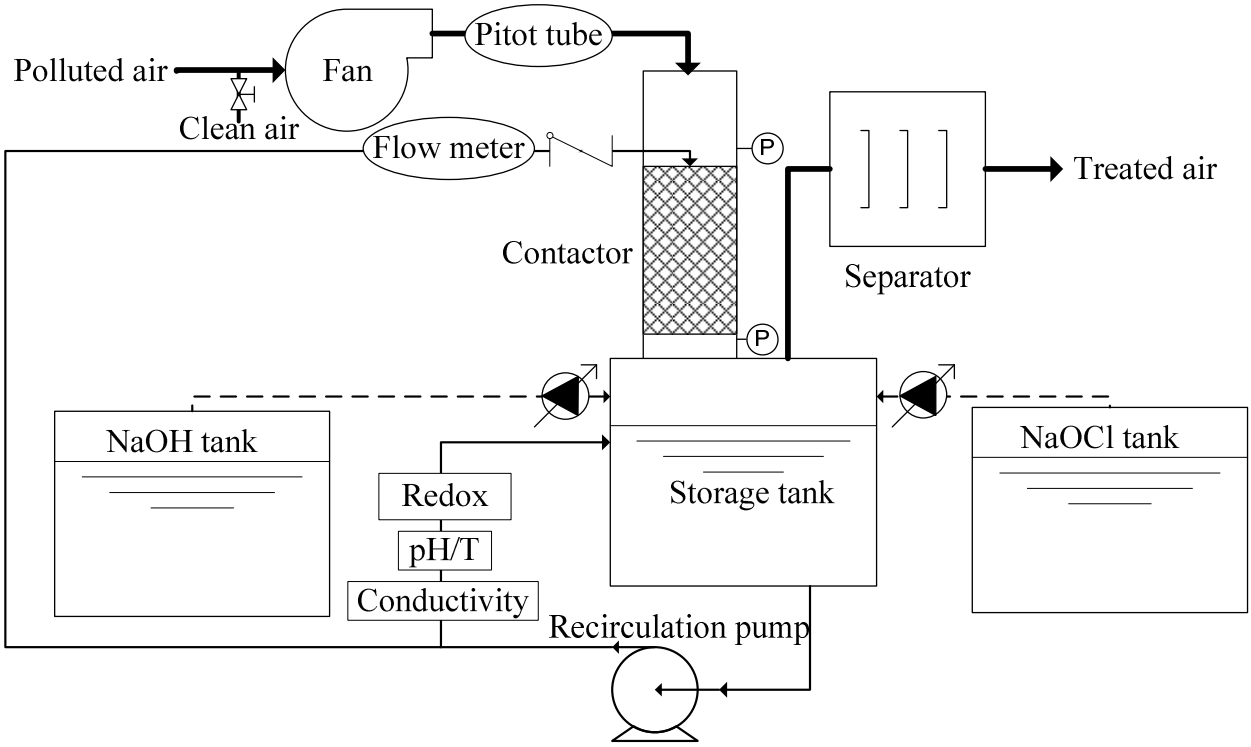
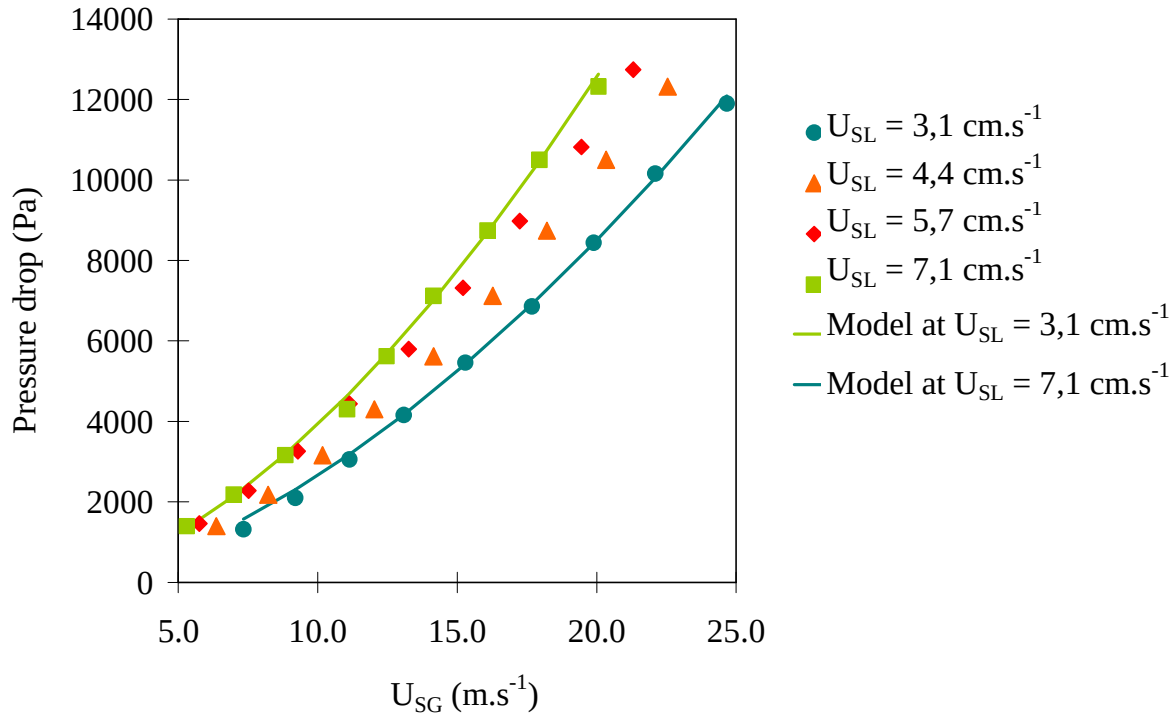

Polluted air
Fan
Pitot tube
Clean air
Flow meter
P
Treated air
Contactor
Separator
P
NaOH tank
Redox
pH/T
Conductivity
Storage tank
NaOCl tank
Recirculation pump

Figure 1



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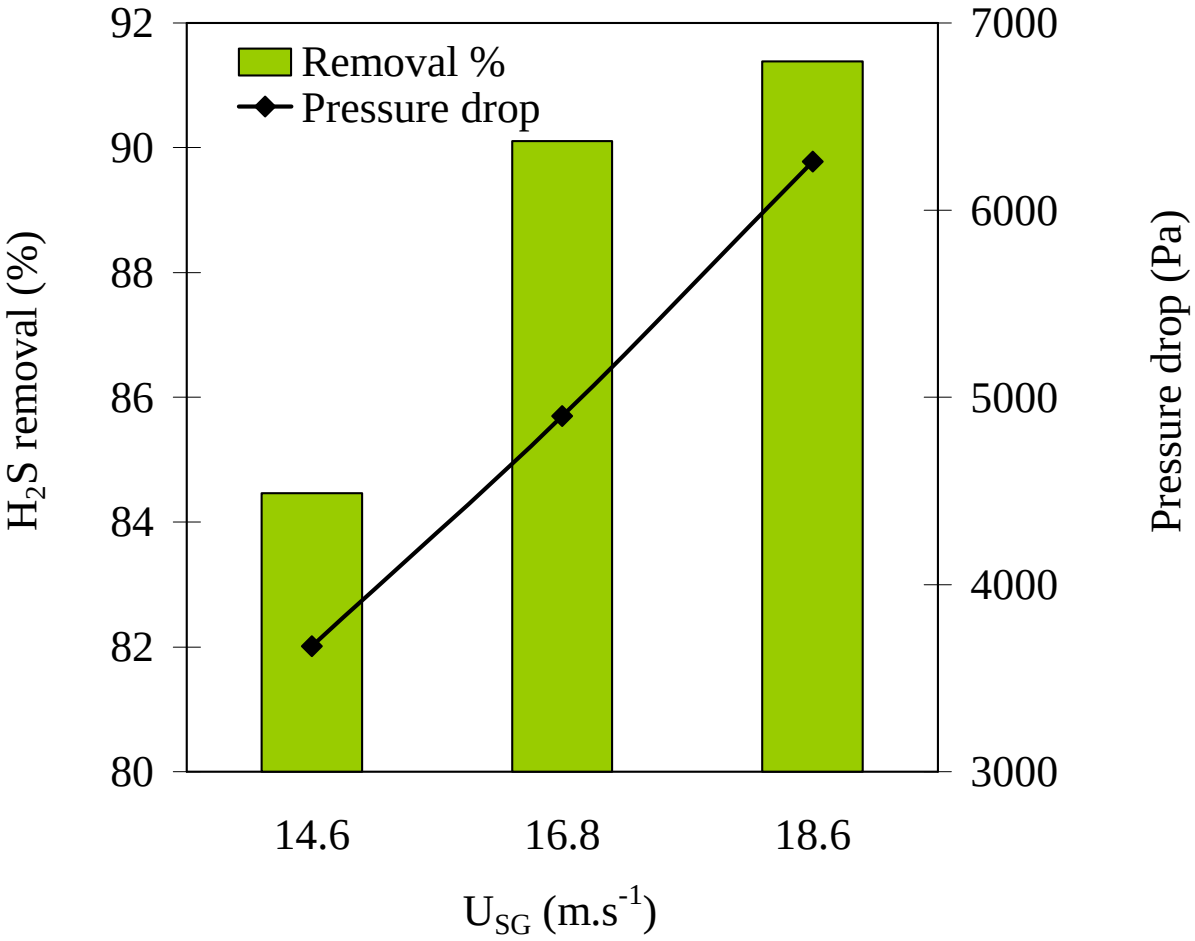

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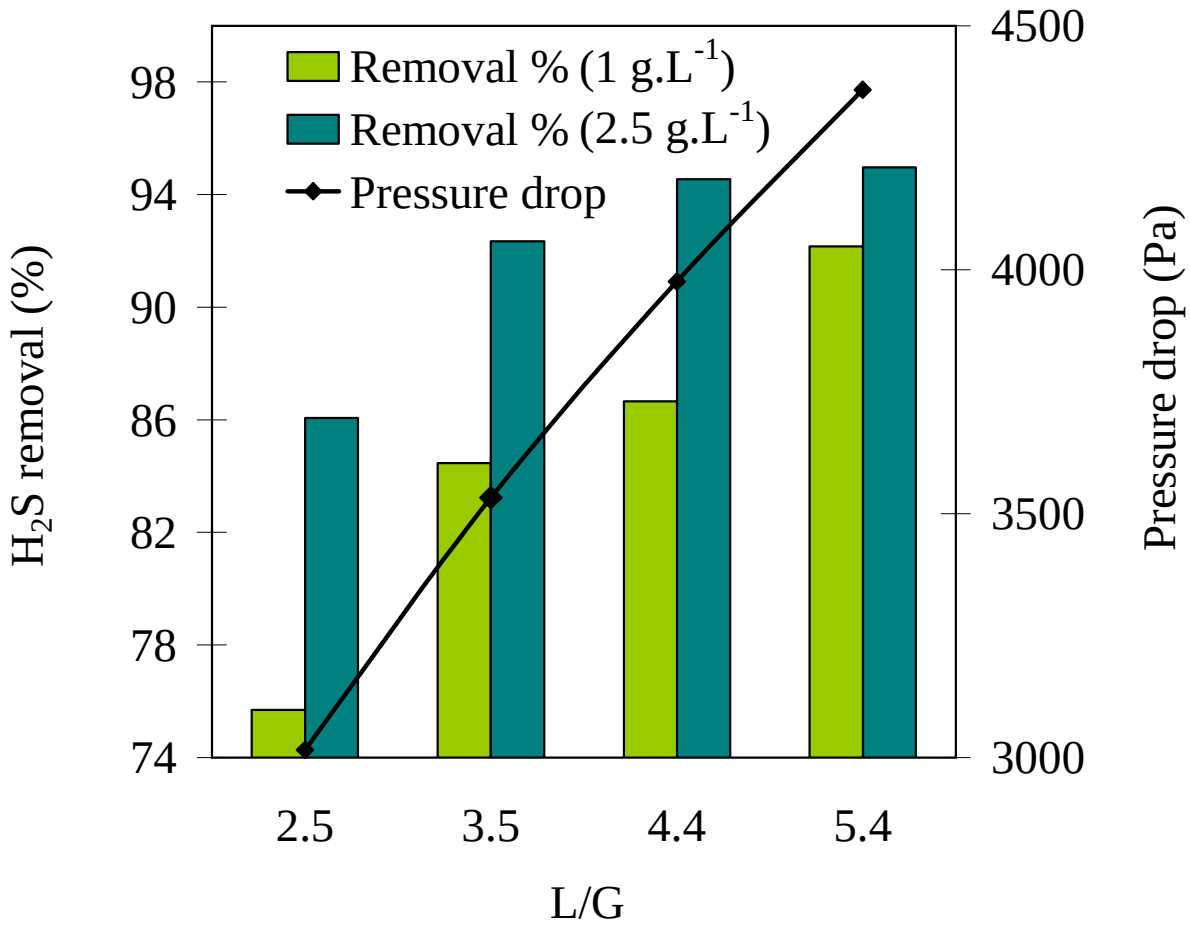
Figure 3



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389 Figure 4

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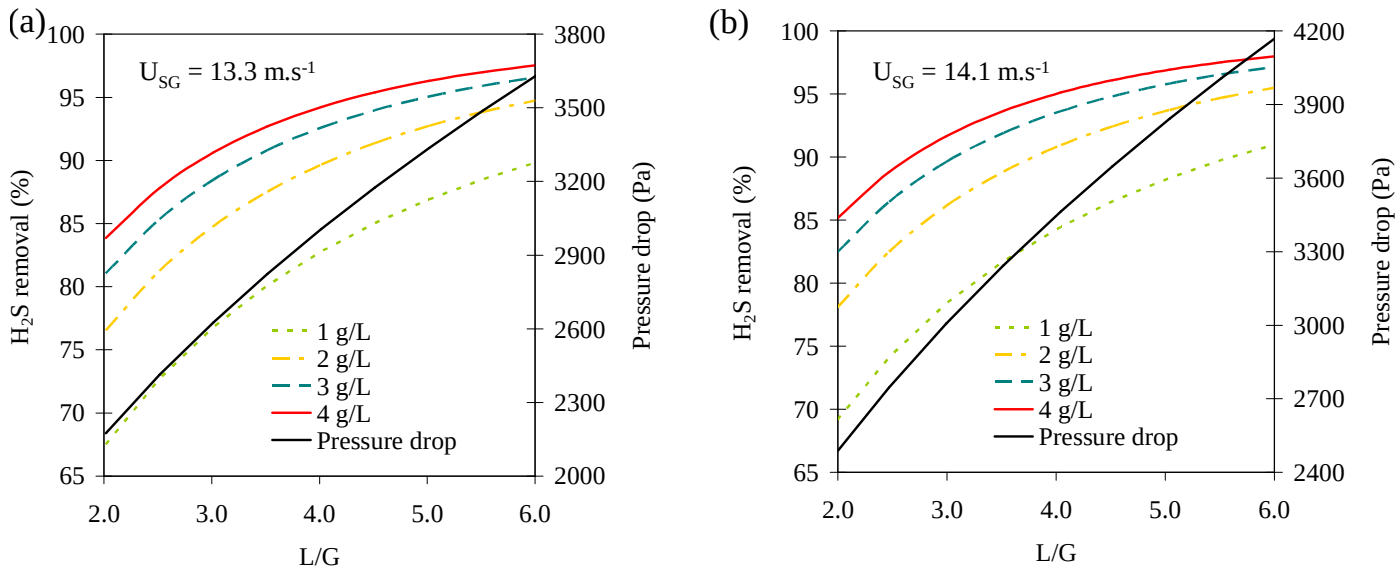

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392 Figure 5

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Table 1. Hatta range values (considering $k_L = 10^{-4}$ m.s^{-1}) and results of the numerical fitting for several values of k_{ox}.

k_{ox} (L.mol^{-1}.s^{-1})	1.0×10^6	6.0×10^6	1.0×10^7	1.0×10^8	5.0×10^8
Hatta range	80-116	195-285	250-370	790-1 160	1 770-2 600
A	205.06	146.98	118.43	47.67	25.85
α	1.61	1.45	1.44	1.37	1.21
β	0.59	0.61	0.61	0.62	0.64
k_G (m.s^{-1})	0.14	**0.24**	0.31	0.85	2.07
a^0 average (m^2.m^{-3})	3 636	**1 575**	1 225	398	135
$k_G a^0$ average (s^{-1})	510	**378**	380	338	277
R^2 (%)	97.44	97.97	97.99	98.06	97.94
Average error (%)	0.83	0.72	0.71	0.67	0.68